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MEASUREMENTS AND MODELING OF DIRECT BED SHEAR STRESS UNDER SOLITARY WAVES

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Abstract: *Solitary waves and solitary bores that represent tsunamis were generated in tsunami wave flume at the Gordon McKay laboratory, The University of Queensland, Australia. Direct bed shear stress was measured using a shear cell apparatus. The solitary wave characteristics were measured using ultrasonic wave gauges and free stream velocities were measured using an Acoustic Doppler Velocimeter. These measurements were carried out in laminar and transitional flow regimes (~10^4 < Re < ~10^5). This sort of data is sparsely available in literature. In the absence of direct measurements, shear stress is indirectly estimated using velocity profiles and friction factors. However, this indirect method has its limitations, e.g., under unsteady hydrodynamic conditions and relatively large roughness. More than 165 experimental runs comprising solitary waves and bores were carried out over a smooth flat bed with wave height to water depth ration varying between 0.12 and 0.69. Analytical modeling was carried out to predict shear stresses using FFT and convolution integration methods on free stream velocities. This paper presents details on measurements and modeling results of solitary wave induce bed shear stresses.*

Keywords: *tsunami; bed shear stress; shear cell; friction factors.*

INTRODUCTION

With depleting natural resources over the land there has been an increased activity offshore for oil and gas exploration and exploitation around the globe. The search for such natural resources in farther and deeper oceanic regions necessitates understanding the effects of potential hazards on the seabed so as to understand the forces generated on subsea infrastructure. Tsunamis are one such potential hazard that has severe and direct effect on the subsea structures. The 2004 Indian Ocean tsunami not only devastated the coastal regions of Indonesia, India and other countries, but also increased awareness about tsunamis and there has been a surge in various aspects of research and development pertaining to the tsunami science. There were about 15 significant tsunamis since the 2004 Indian Ocean event till March 2010 and still there were casualties and devastation at many places, e.g., in Haiti,

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Chile, etc. Though the aftereffects of tsunami on the coastline are evident, its effect on seabed and submarine structures during its propagation is not well documented in the literature. In view of this, studies were initiated at the University of Queensland, to understand the effects of tsunami propagation on seabed and submarine features, especially continental slopes and submarine pipelines.

Solitary waves have been commonly used in the literature to represent tsunamis (Goring 1979; Madsen et al. 2008; Synolakis and Bernard 2006). Undular bores and solitary waves were observed during the December 2004 Indian Ocean tsunami event and these were simulated in a model study using the fully nonlinear dispersive method (FNDM) and the Korteweg-deVries (KdV) equation (Grue et al. 2008). Though the propagation of tsunamis can be modeled in near real time (Tang et al. 2009), details on bed shear stresses and pressure gradients that are exerted over the seabed are not well documented. Sediment transport modeling essentially requires bed shear stresses which is mostly derived indirectly from the velocity profiles (Nielsen 1992) or from direct measurements. Bed shear stress in wave flumes or open channels are directly measured using shear plates (Barnes and Baldock 2007; Grass et al. 1995; Huo et al. 2007; Ippen et al. 1955; Riedel 1972; You and Yin 2007) or thermal techniques using hot film probes (Sumer et al. 1993) or indirectly from the measurements of velocity profiles using Laser Doppler Velocimeters (LDV) or Particle Image Velocimetry (PIV) techniques or by Acoustic Doppler Velocimeters (ADV) and estimate the shear stress using quadratic drag law (Eq.1) (Jensen et al. 1989; Liu et al. 2007).

METHODOLOGY

Investigations were carried out at the wave flume at the UQ Gordon McKay hydraulics laboratory. A piston wave maker, with a stroke length of about 1.2 m was used. The laboratory model setup includes a 1 in 10 slope considered as the continental slope and a flat bed region depicting the continental shelf region apart from the flat bed before the slope to represent offshore region (Fig. 1). A shear plate apparatus with fundamental design of Grass et al. (1995) is used to measure the bed shear stress by measuring displacement of the shear plate placed flush with the bed, due to the force exerted by the waves. More details of the shear plate apparatus has been described in Barnes et al. (2009). Ultrasonic wave gauges were used to measure the water surface elevations and an ADV is used to measure the free stream velocities about 1 cm above the bed. High response pressure transducers were used to measure the pressures near the bed on either side of the shear plate. The distance between the wave paddle and the shear plate is 8 m and the distance between the shear plate and the toe of the slope is 1.8 m. The length of the sloped region is 1.6 m and further the bed is flat for more than 5 m. Experiments were carried out with the flume bed made of impermeable smooth marine plywood (hereinafter referred to as smooth bed).

Solitary waves and bores were generated using two methods viz., (1) by utilizing the solitary wave generation method as per Goring and Raichlen (1980) and (2) by using error functions to generate impulse waves as presented in Baldock et al. (2009). By varying the stoke length and the speed of the piston, solitary waves and bores of different amplitudes could be generated. Typical profiles of the wave paddle displacement and the waves generated for non-breaking and breaking waves respectively are shown in Fig. 2 and Fig. 3.

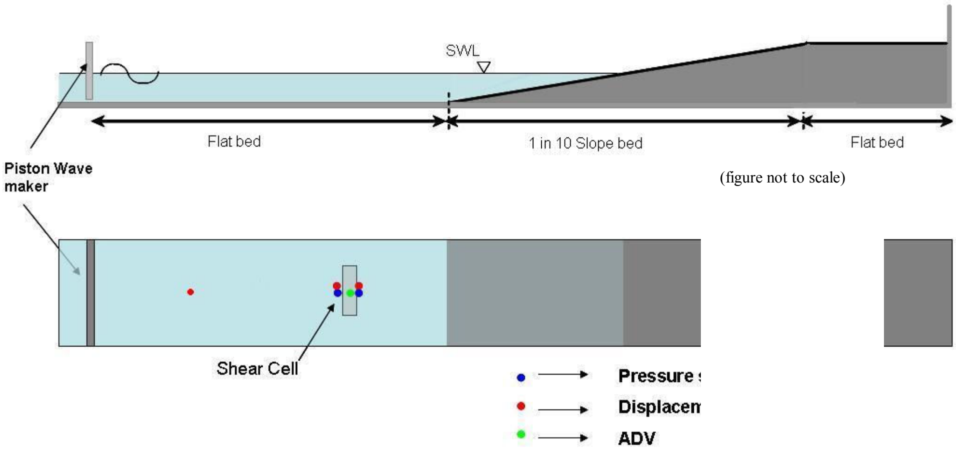
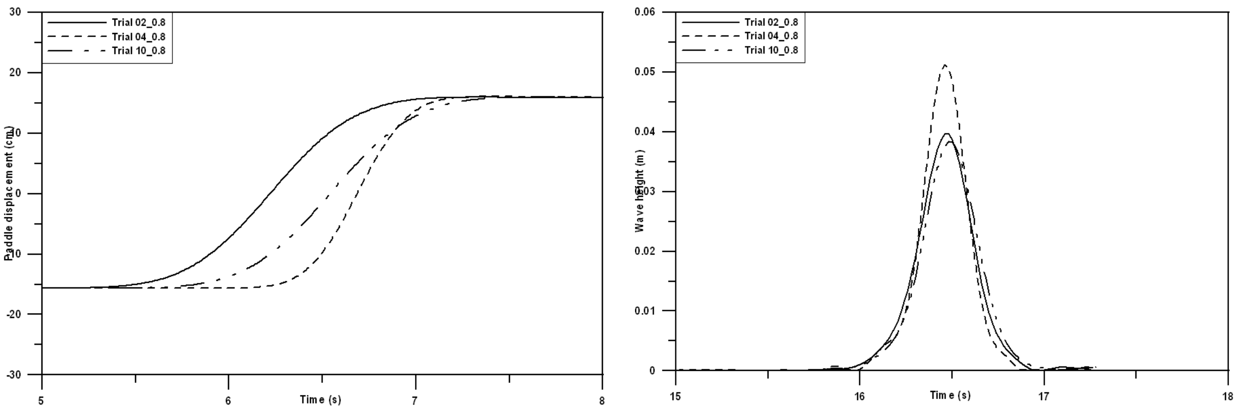


Fig. 1. Experimental setup.

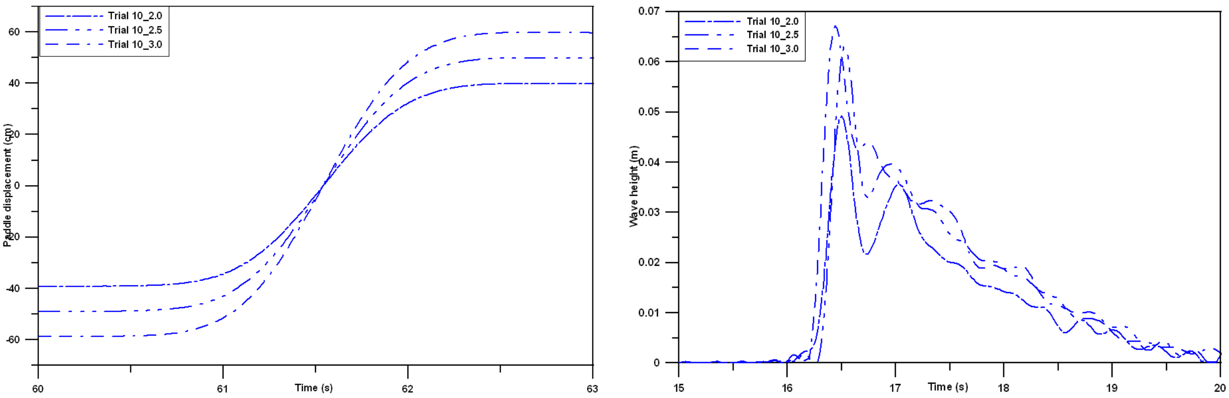


(a) (b)

Fig. 2. Non-breaking solitary waves (a) paddle displacement (b) wave profile.

For each of the wave generated, (a) bed shear stress (b) water surface displacement (wave height) (c) velocity outside the boundary layer (d) pressure near the bed are measured. In all 84 tests in duplicate were conducted for the smooth bed case, wherein 49 tests are non-breaking solitary waves and 35 are breaking solitary bores.

The data from the wave sensors, pressure sensors, and shear plate displacement sensor as well as the ADV was acquired simultaneously. National Instruments data acquisition system was used to acquire the data from the wave, pressure and shear sensors whereas a proprietary software of Sontek ADV was used to acquire the velocity data. All the sensors and ADV were started synchronously and data was recorded at 50 Hz frequency. The noise from the sensors' raw data was de-spiked and filtered using tools available in MATLAB. This filtered data was used in further analysis as well as for comparison with the theoretical estimates. Wave, current and shear data was considered further for analysis and measured pressure data is not used in the present study.



(a) (b)

Fig. 3. Breaking solitary waves (a) paddle displacement (b) wave profile.

Bed shear stress (τ_b) is often estimated using quadratic drag law (Eq. 1) wherein friction factor (f) and free stream velocity outside the boundary layer (or near bed velocity, u_∞) is used. In cases where the friction is large or under unsteady conditions, this method of estimating shear stress using a single friction factor fails. In view of this, direct measurement of shear stress or modeling of shear stresses using alternate methods is preferred. To model the shear stress from the measured wave and current data, two methods (FFT method and Convolution method) as indicated in Guard et al (2009) were adopted in this study and the same is briefly presented in this paper.

$$\tau_b = \frac{1}{2}\rho f u_\infty^2 \tag{1}$$

For horizontally uniform flows in laminar boundary conditions, the laminar shear stress on top of the shear plate is calculated using Eq. 2.

$$T(\omega) = \rho\sqrt{i\nu\omega}U_\infty(\omega) \tag{2}$$

where, $T(\omega)$ and $U_\infty(\omega)$ are the Fourier transforms of $\tau_b(t)$ and $u_\infty(t)$, ω is angular frequency, ν is kinematic viscosity, ρ is fluid density, i is the imaginary unit and $\rho\sqrt{i\nu\omega}$ is frequency response function. The near bed velocity $U(\omega)$ using appropriate transfer function can be calculated using Eq. 3. The laminar bed shear stress is thus calculated from the measured near bed velocity just outside the boundary layer $u_\infty(t)$.

$$U(\omega) = H(\omega)\frac{\omega}{\sinh(kh)} \tag{3}$$

The total shear stress (τ_{TOTAL}) measured by a shear plate placed on the bed (Eq. 4) is a resultant of the shear stress (τ_b) due to wave as well as the pressure gradient force generated by the free surface slope of the wave (Barnes et al. 2009; Grass et al. 1995; Riedel 1972). The pressure gradient force (τ_{pr}) can be estimated directly by measuring the pressure difference between two different locations across the shear plate or by estimating the equivalent force per unit area of the shear plate generated by the pressure gradient force (Eq. 5).

$$\tau_{TOTAL} = \tau_b + \tau_{pr} \tag{4}$$

$$\tau_{pr} = \frac{\partial p}{\partial x}\frac{Volume_{plate}}{Area_{plate}} = \frac{\partial p}{\partial x} thickness_{plate} \tag{5}$$

If hydrostatic conditions are considered Eq. 5 reduces to Eq. 6 and for non-hydrostatic conditions, making use of the expression for pressure variation under sine waves the pressure force can be calculated as shown in Eq. 7.

$$\tau_{pr} = \rho g \frac{\partial \eta}{\partial x} thickness_{plate} \tag{6}$$

$$P(\omega) = \rho g h \frac{H(\omega)}{\cosh(kh)} \tag{7}$$

where, H(ω) and P(ω) are the Fourier transforms of surface displacement η(t) and pressure p(t).

The other method of calculating the shear stresses from the free stream velocity, without using frequency domain, is by using Convolution integrals. The shear stress in time domain is obtained by applying Convolution integration over the velocity in time domain. This method is detailed in Guard et al.(2009). Torsvik and Liu (2007) describe techniques for efficient calculations of convolution integrals. Shear stress, using the Convolution method, is estimated using Eq. 8.

$$\tau(t) = \rho\sqrt{\frac{\nu}{\pi}}\int_0^t \frac{\partial u_\infty / \partial t'}{\sqrt{t-t'}} dt' \tag{8}$$

Similarly, the pressure can be obtained using the following appropriate impulse response function as in Eq. 9 and since the wave height is measured in time domain, it can be transformed into spatial domain by assuming that the wave travels with constant speed thereby dt = dx / sqrt(gh).

$$p(t) = \rho g h + \int_{-3h}^{3h} \frac{\eta(x)}{2h\cosh\frac{\pi(x-x')}{2h}} dx \tag{9}$$

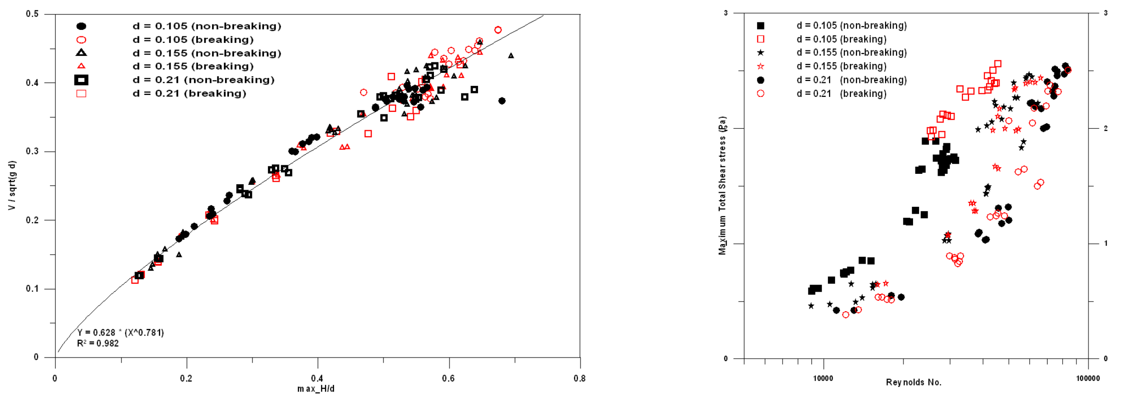
The two methods briefly described above do not involve use of friction factors. However, friction factors can be calculated from the estimated shear stresses as well as measurements by using Eq. 1. These estimated friction factors are overlapped on to the wave friction factor diagram of Kamphuis (1978). Since the shear stress, velocity and the wave height vary with time, the estimated friction factors do vary with time. In order to compare with the earlier literature, friction factors corresponding to the maximum shear stress are used. The maximum value of Reynolds number (RE) is estimated using the measured maximum velocity (U) and the excursion length of water particle (A) and kinematic viscosity (ν) as RE = A U / ν.

RESULTS AND DISCUSSION

Measured direct bed shear stresses, wave heights and free stream velocities for various test cases of solitary waves and bores are analysed and the maximum values of wave height, shear stress, velocity are presented in graphical form (Fig. 4). The wave height to water depth ratio is observed to vary exponentially with the velocity ratio irrespective of the wave breaking, however, for H/d more than 0.5 the velocities were observed to have a spread (Fig. 4a). The present experiments were observed to be in lower limit of rough turbulent region and mostly in the transition regime as per the wave friction diagram of Kamphuis (1978).

Table 1. Details of the range of experiments

Parameter	Minimum	Maximum
Water depth (m)	0.105	0.21
H/d	0.12	0.69
Reynolds Number	8976	83821
$U_{\max} / \sqrt{g.d}$	0.113	0.478
$\tau_{max}(N.mm^{-2})$	0.385	2.562



(a) (b)

Fig. 4. (a) Maximum H/d vs maximum $U_{max}/\sqrt{(gd)}$ (b) Reynolds number vs Maximum total bed shear stress.

The measured parameters viz., wave height, free stream velocity, bed shear stress, the derived parameters viz., friction factors, and the estimated parameters of bed shear stress using the two methods and the velocity for non-breaking waves are presented in Fig. 5a and for breaking waves are presented in Fig. 5b. Wave height was measured on the leading as well as the trailing edge of the shear plate to calculate the pressure gradient that would be deducted from the total shear stress in order to obtain the laminar shear stress or skin shear. The shear stress is observed to be out of phase with the free stream velocity wherein the stress leads the velocity. Also the shear stress changes its sign even though the free stream velocity is positive all the while and this is attributed to the driving pressure gradient wherein the pressure gradient becomes positive during the deceleration phase (Sumer et al. 2008). The change in sign of shear stress for breaking solitary bore does not change significantly unlike the non-breaking wave (Fig 5b). Free stream velocity estimated from the wave height match very well with the measured velocity both for the breaking as well as non-breaking waves for velocities up to 0.5 m/s and overestimates are predicted for higher velocities compared to measurements (Fig. 6a). Shear stresses estimated using two models outlined in this paper showed that the total shear stress can be estimated from the free stream velocity profile to a higher degree of accuracy using the convolution technique compared to the FFT method for the non-breaking solitary waves (Fig. 6b&6c).

From Eq. 1, time series of wave friction factor for each of the test case is estimated using the measured shear stress and corresponding measured velocities (Fig 5a&5b) and the friction factor corresponding to the maximum shear stress is considered in further analysis. These friction factors were estimated both for the total shear stress (including the pressure gradient force) (Fig. 7a) and skin shear (excluding the pressure gradient force) (Fig. 7b). Irrespective of the breaking condition the wave friction factors corresponding to the skin shear stress were of similar magnitude whereas the wave friction factors, derived from total shear stress, corresponding to the breaking waves were observed to have slightly larger estimates, possibly due to the pressure gradient forces being larger for breaking waves.

CONCLUSIONS

Solitary waves and solitary bores were generated in a flume and the direct bed shear stresses were measured in laminar and transition regimes. Shear stress is observed to lead the free stream velocity both in non-breaking solitary waves as well as solitary bores. Velocity estimates using the wave heights were found to be accurately predictable up to 0.5 m/s and estimates were over predicted for higher velocities. Two models were successfully applied to predict the shear stresses from the measured free stream velocities and the method of convolution is found to predict the bed shear stresses better than the FFT method. The friction factors derived from the skin shear stresses and free stream velocity indicate that the breaking solitary wave and the non-breaking waves do not exhibit distinct variations in the friction values unlike the friction factors derived from the total shear stresses indicating the dominant influence of pressure gradients.

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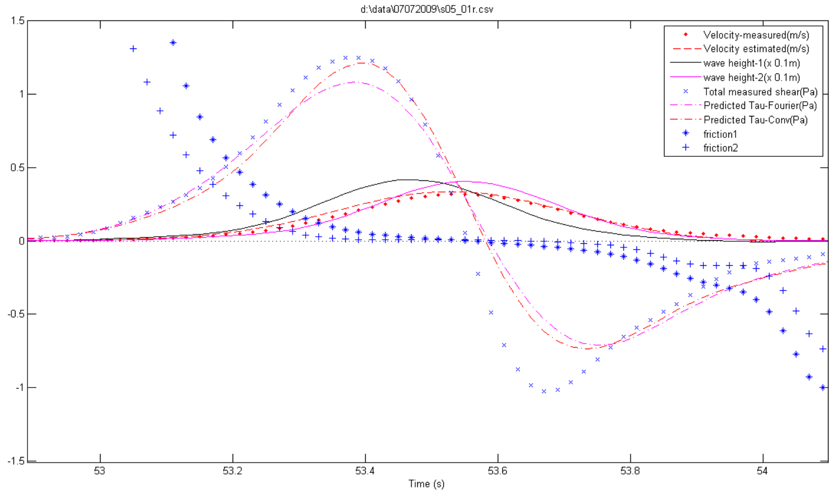
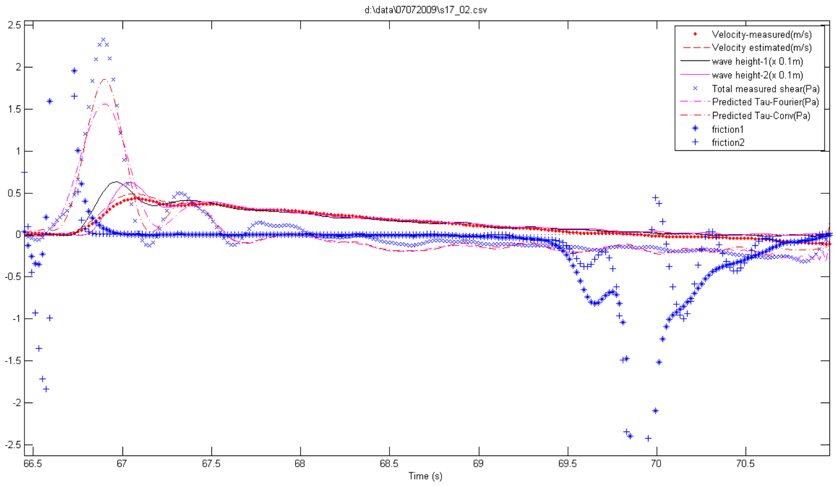
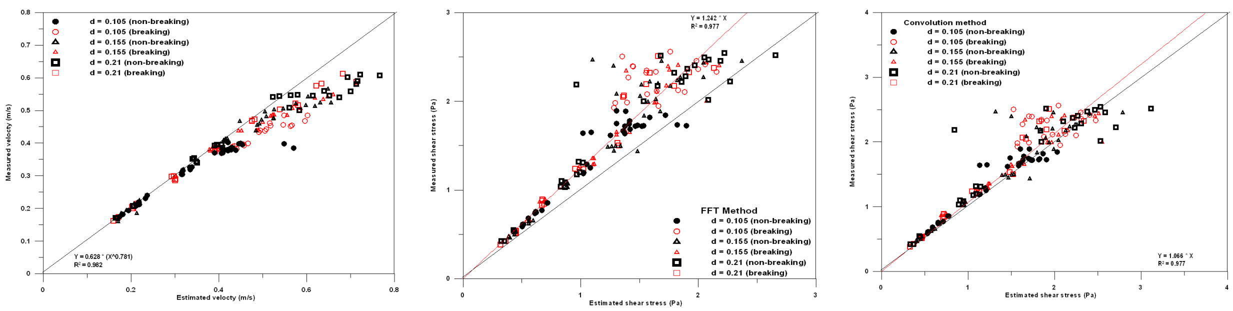


(a)



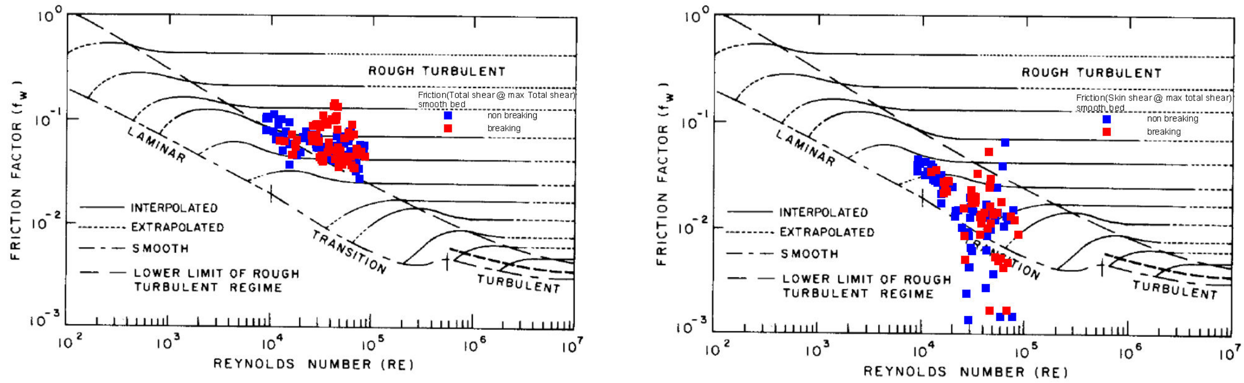
(b)

Fig. 5. Measured and modeled parameters for (a) non-breaking solitary wave (b) breaking solitary bore.



(a) (b) (c)

Fig. 6. Measured and estimated parameters (a) free stream velocity (b) Shear stress (Total) using FFT and (c) Shear stress (Total) using Convolution method.



(a) (b)

Fig. 7. Estimated friction factors overlayed on Kamphuis (1978) plot (a) Total shear stress (b) Skin shear stress.

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